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PRODUCTION OF BIMETALLIC AND TRIMETALLIC MATERIALS BY EXPLOSION WELDING AND ALLIED PROCESSES

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ABSTRACT

The paper and talk deal with the research results in the field of welding the combined metals such as Ti-Cu, Ti-Al, Sn-Cu, Al-Mg alloy, Monel-steel, Pb-steel, AlSi alloy-Cu, Ta-Monel, Ta-Stainless Steel, Monel-Ta, steel-Ti-Al, steel-Cu-Al, etc., as well as the processes allied. The combinations that are not mentioned in the paper will be presented during the talk.

The results were attained in collaboration with the Research Institute of Industrial Chemistry, Pardubice-Semtin (Czech Republic) and the Slovak University of Technology, Department of Welding, Faculty of Materials Science and Technology, Trnava (Slovak Republic). The bimetals and trimetals were produced using the Semtex S explosive. The quality of joints was evaluated by ultrasonic detection, optical microscopy, microhardness measurements and X-ray microanalysis.

KEY WORDS

Explosion Welding, Explosive, Welding Metals, Welding Parameters, Bimetal, Trimetal, Quality Control.

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INTRODUCTION

Regarding its productivity, the explosion welding is not the technology that could compete with such technologies as GMAW, resistance welding, laser welding, etc. In spite of that, it has an irreplaceable position in fabrication of special materials. Figs. 1a and 1b show the worldwide trends in the field of research and development of special materials and technologies, where the materials produced by explosion are given within multi-materials and the explosion welding belongs to the group named Other Welding Processes within individual welding technologies [1].

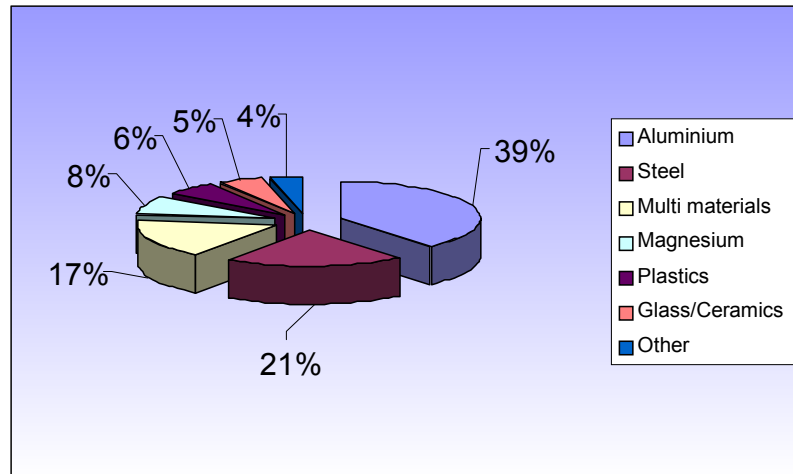


Fig. 1a. Fields of Research / Materials [1].

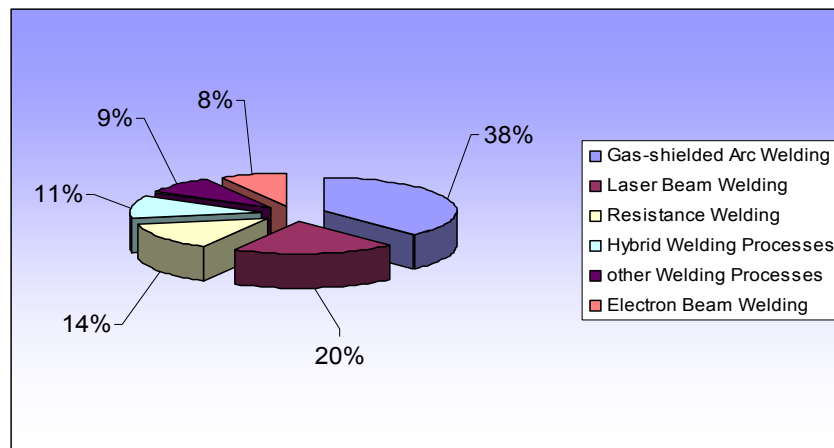


Fig. 1b. Fields of Research / Welding [1].

In former Czechoslovakia, explosion welding had a rich history, mainly owing to merits of the Research Institute of Industrial Chemistry in Pardubice - Semtin, which successfully co-operated, besides many others, with the Faculty of Mechanical Engineering (Department of Physical Metallurgy, Welding and Founding) of the Slovak Technical University in Bratislava and later also Explosia Inc., RIICH Pardubice with the Welding Department, and the Faculty of Materials Science and Technology of the Slovak University of Technology in Trnava. This co-operation resulted in several research tasks, which were implemented into technical practice, such as:

- Al-steel bimetal for electrolyzer for manufacture of aluminum and building a workplace for explosion welding (ZSNP Žiar nad Hronom, SR), including the mass surfacing of 16 bimetal on one firing, Ta-Cu targets for sputtering in micro electronics (TESLA Lanškroun, CR), wear-resistant splice plates made of Hadfield steel - cast steel for Wagon Works (Vagónka Poprad, SR),
- bimetallic Cu-ALSi clamps for high voltage and very high voltage electricity lines (Elektrovod Kremnica, SR),
- bimetallic contact screws for cars (PAL Kroměříš, CR), including mass surfacing (500 pieces on one firing),
- Pb-steel bimetal for the Chemical Works (former "Dynamit" plant, SR),
- grey cast iron - structural carbon steel bimetal etc.
- Cu-Al 99.9999 bimetal (M.R.C. New York) and others.

Bonding of such bimetal as Ti-Cu, Ti-Al, Sn-Cu, Al-Mg alloy, Cu-Mg alloy, Monel-stainless steel, Monel-Ta, and also trimetal such as steel-Cu-Al and steel-Ti-Al was also solved. Many experiments in the field of splitting, strengthening metals etc. were performed at RIICH, Explosia Plant in Pardubice, CR.

EXPLOSION WELDING

The well-known Semtex explosives are used within the Czech and Slovak Republics for technological processing of metals. In the past, Semtex S 25 explosive was mostly used for welding. At present, Semtex S 30 and also other explosives adapted to physical and mechanical properties of welded materials are being used. The characteristics of selected Semtex type explosives are given in Table 1.

Table 1. Explosives for hardening and cladding (15).

Parameters	Unit	SEMTEX® S 30	SEMTEX® 10-SE
Type		Powder	Plastic
Explosion heat	kJ/kg	1,277	3,992
Swath volume	dm ³ /kg	420	944
Oxygen balance	%O ₂	-3	-62.6
Detonation velocity	m/s	2,200	7,000
Trauzl test	ml	--	--
Brisance by Hess	mm	10	20
RWS (blasting gelatine)	%	12	72
Temperature of explosion	°C	1,023	2,600
Transmission of detonation	cm	--	--
Density	kg/m ³	--	1,450
Water resistance	-	no	excellent
Smallest diameter permitted	mm	--	1.5
Loose mass	G.mm ⁻³	1.1	--

Approximate dependence of detonation velocities of Semtex S explosives on their thickness is given in Fig. 2.

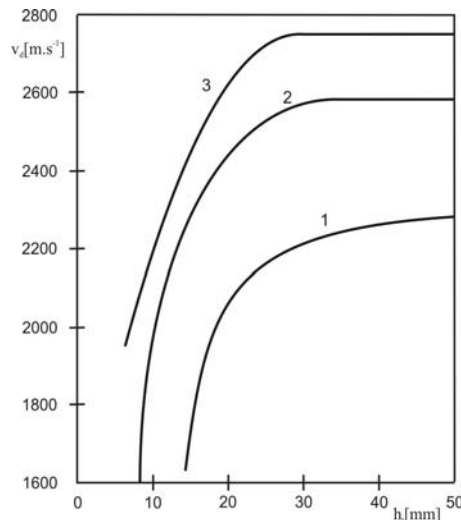


Fig. 2. Dependence of detonation velocity v_d on explosive thickness h (9).
 (1- Semtex S 25 at $\zeta_t = 1.20 \text{ g. cm}^{-3}$, 2 - Semtex S 30 at $\zeta_t = 1.15 \text{ g. cm}^{-3}$, 3 - Semtex S 35 at $\zeta_t = 1.10 \text{ g. cm}^{-3}$)

In most cases, parallel arrangement of welded materials (welding assembly) was applied, as shown in Figs. 3a, 3b.

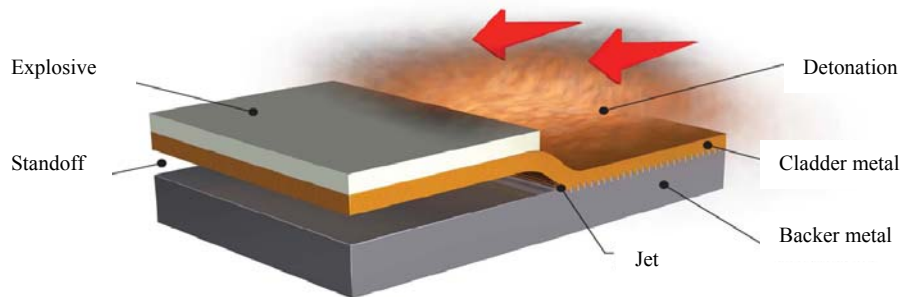


Fig. 3a. Principal scheme of explosion welding (9).

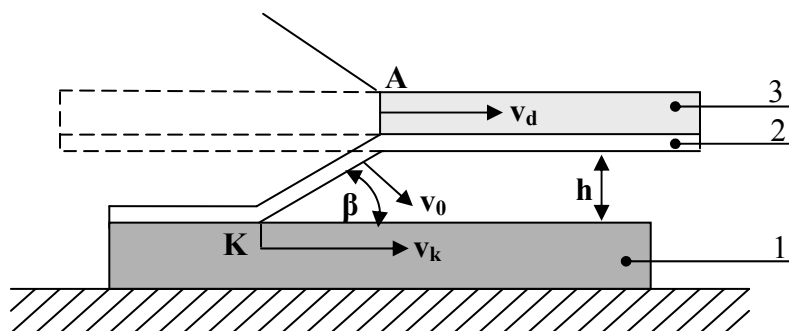


Fig. 3b. Kinematic scheme of explosion welding (3,9).

As known, the main welding parameters are v_d , v_0 , v_k , h , β . From Fig. 3b, the basic relationships for Semtex S 25 explosive (which is now preferentially used at RIICH

Explosia Inc. Pardubice) can be derived. By the authors Chládek, L. and Vacek, J., the following v_d and δ parameters were suggested:

$$V_d = \left(3256 - \frac{114110}{h_t^2} \right) \cdot (\zeta_t - 0,325) \quad [\text{m.s}^{-1}; \text{mm, g. cm}^{-3}] \quad (1)$$

for $10 \leq h_t \leq 35$; if $h_t > 35$ mm, $h_t = 35$ mm – (upper limit layer);

$$\delta = \frac{0,4007 - 0,004725h_t}{0,3485 + \frac{1}{\omega}}, \quad (2)$$

where h_t is the explosive thickness, ρ_t – explosive density, ω - weight proportion of the charge to accelerated material.

For better apprehension, let us state that the detonation velocities of explosives suitable for explosion welding usually vary within the range from 900 to 3500 m.s⁻¹. The impact velocity of material accelerated by explosive usually attains 300 to 1500 m.s⁻¹ on the path formed by distance spacing. The necessary spacing between the plates and/or opening and the outer wall of expanded tube varies within several tenth of mm up to several mm. The entire event takes place within the time in order of tens to hundreds microseconds (μs). Weldability of various materials is given in Table 2.

Manufacturing of composite and multilayer sheet billets of heterogeneous metal and alloys of up to 12 sq. m. area, front 0.5 to 700 mm thickness can be carried out directly by welding as well by combination of welding and rolling. The most promising joints can be obtained by joining the following pairs of metals: titanium alloys + steel, aluminum alloys + steel, zirconium alloys + steel, magnesium alloys + steel, nickel alloys + steel, copper alloys + steel, aluminum alloys + titanium (alloys), aluminum alloys + magnesium, aluminum alloys + copper, lead + steel, lead + copper, niobium + zirconium alloys and others (16).

MATERIALS FOR REPARATION OF MULTILAYER ARMOURS

Multilayer metal structure is mostly prepared as a three-layer material. Armour steel is the base of multilayer material. Top-layer is the material the high hardness of which can be achieved while preserving certain degree of toughness. The interlayer is the material which enables armour and tool steel to be joined, furthermore, it enables heat processing, it works as a diffusion barrier, balances different dilatation of the materials used for the base and top layers, prevents from propagation of cracks, ensure integrity of the armour on repeated ballistic loading and, in an ideal case, it contributes to increased ballistic resistance.

For the base armour layer (backer metal), it was possible to use commercially available armour steel. Cladder metal for the top layer of the multilayer armour was tool steel. Nickel alloys were the material used for interlayer. Fig. 4 shows the structure of the weld interface.

Table 2. Weldability of materials in explosion welding (14).

	Zirconium	Vanadium	Tungsten	Titanium	Tantalum	Steel alloy	Steel, mild	Steel, Stain	Silver	Rhenium	Platinum	Palladium	Niobium	Ni alloy	Nickel	Moly alloy	Molybdenum	Magnesium	Kovar	Indium	Hafnium	Gold	Copper alloy	Copper	Beryllium Cu	Al Bronze	Al alloy	Aluminum
Aluminum	X	X	X	X	X	O	X	O	X	X	X	O	X	O	O	X	X	O	O	O	X	X	X	X	O	O	X	X
Al alloy	X	X	X	X	X	O	O	O	X	X	X	O	X	O	O	X	X	O	O	O	X	X	X	X	O	O	X	X
Al Bronze	O	X	O	O	X	X	X	O	O	O	X	O	X	O	O	X	X	O	X	X	X	X	X	X	O	X	X	X
Beryllium Cu	O	X	O	O	X	O	X	O	X	O	X	O	X	O	O	X	X	O	O	O	O	X	X	X	O	X	X	X
Copper	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	O	X	X	X	X	X	X	X	X	X	X
Copper alloy	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	O	X	X	X	X	X	X	X	X	X	X
Gold	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	O	X	X	X	X	X	X	X	X	X	X
Hafnium	O	X	X	O	X	X	X	X	X	X	X	X	X	O	O	X	X	O	X	X	X	O	X	X	X	X	X	X
Indium	X	X	X	O	X	O	O	X	O	O	O	X	O	O	X	X	O	X	X	X	X	X	X	X	X	X	X	X
Kovar	O	X	X	O	X	X	X	X	O	X	O	X	X	X	X	X	O	X	X	X	X	X	X	X	X	X	X	X
Magnesium	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Molybdenum	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Moly alloy	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Nickel	X	X	X	X	X	X	X	X	O	X	O	O	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Ni alloy	O	X	X	O	X	X	X	X	X	O	X	O	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Niobium	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Palladium	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Platinum	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Rhenium	O	X	X	O	X	O	O	O	O	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Silver	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Steel, Stain	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Steel, mild	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Steel alloy	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Tantalum	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Titanium	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Tungsten	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Vanadium	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Zirconium	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

METAL COMPATIBILITY CHART

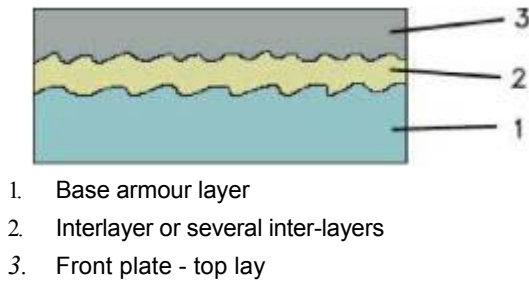
- X Direct Bond, No Interlayer
- O May Require Interlayer

Functional samples were prepared by means of explosion welding technology (EWT). In terms of this technology, it is necessary that the materials chosen are available in the form of sheets and plates with properties suitable for cladding (suitable hardness and quality of surface, ductility etc.). The availability of tool steels in the form of sheets is a little worse; some types of tool steels in the form of sheets are commercially unavailable. In such case, it is not possible to use EWT for preparation of functional samples. The tool steel can be prepared in the form of sheet but at relatively high costs, and then EWT becomes rather ineffective.

Selection of materials is influenced by the fact, that multilayer structure is heat processed as the whole. By heat processing, the quality shall be achieved both of base armour layer (high hardness and toughness) and top layer (above all hardness). At the same time, the process must not lead to the degradation of the material (materials) of interlayer. Usually, the decisive factor is quality heat processing of the top layer, detrimental, however, to the quality of the base armour layer (lower strength and hardness).

THE TESTING OF MATERIALS

The most important part in the development of the materials suitable for ballistic protection is the testing of their ballistic resistance by firing tests, or, potentially, the



1. Base armour layer
2. Interlayer or several inter-layers
3. Front plate - top layer

Fig. 4. Explosive welding: three-layer structure.



testing of their resistance to impact of fragments or effects of mines explosion etc. Figure 5 shows the cross section of the plates after projectile penetration. In addition to the projectile penetration, separation of individual layers of the armour, cracks propagation, spalls formation etc. is also observed and Fig. 6 the monitoring of scratches.

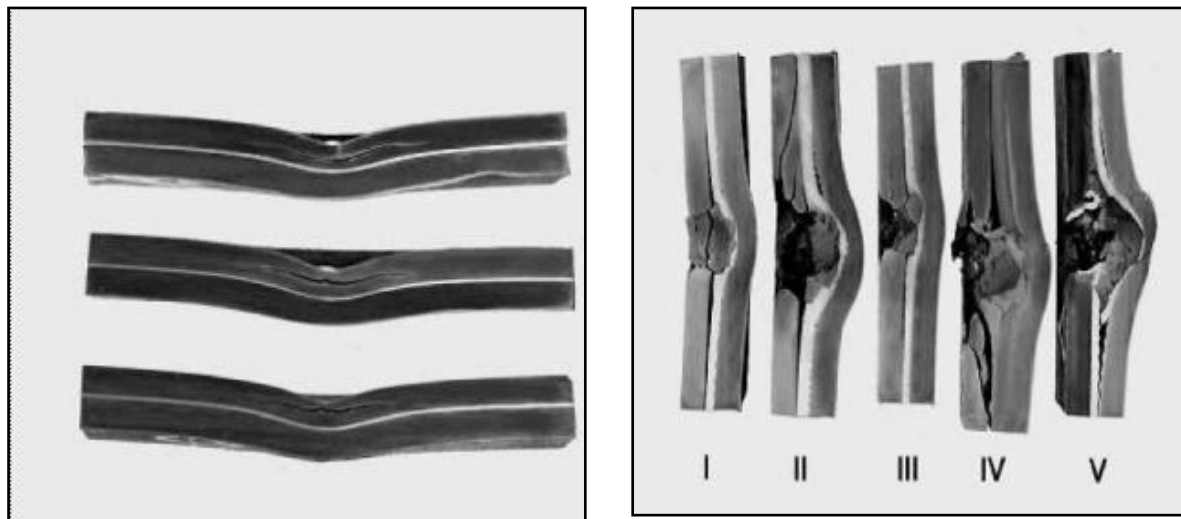


Fig. 5. Cross section of plates after projectile penetration.

NUMERICAL SIMULATION OF EXPLOSIVE WELDING

Numerical simulations (Fig. 7) are the part of the development. The objective is to utilize the simulation to model the actions and optimize the incoming parameters. It is possible to measure tensile stresses, pressures, plastic deformations, velocities, and the possibilities can be evaluated of rise of rupture in the form of spall.

FINAL MANUFACTURING

After verification of needed properties of multilayer structure and definition of suitable materials combination, it is possible to start with manufacturing the multilayer material

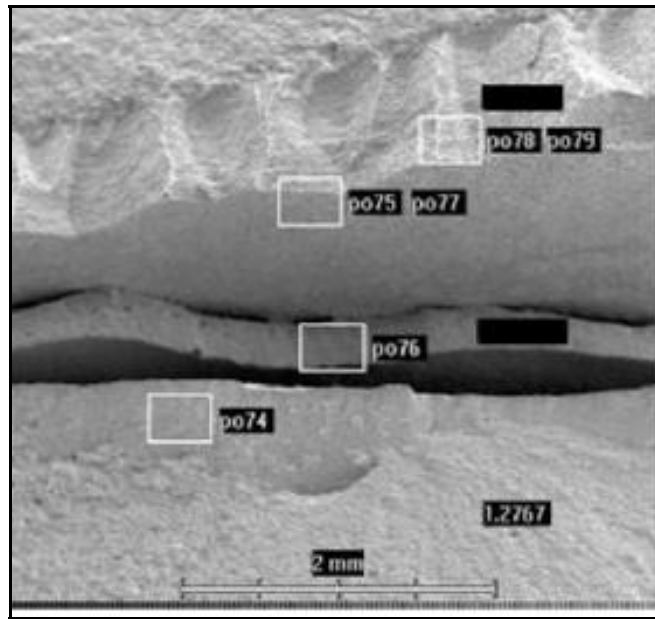


Fig. 6 The monitoring of scratches.

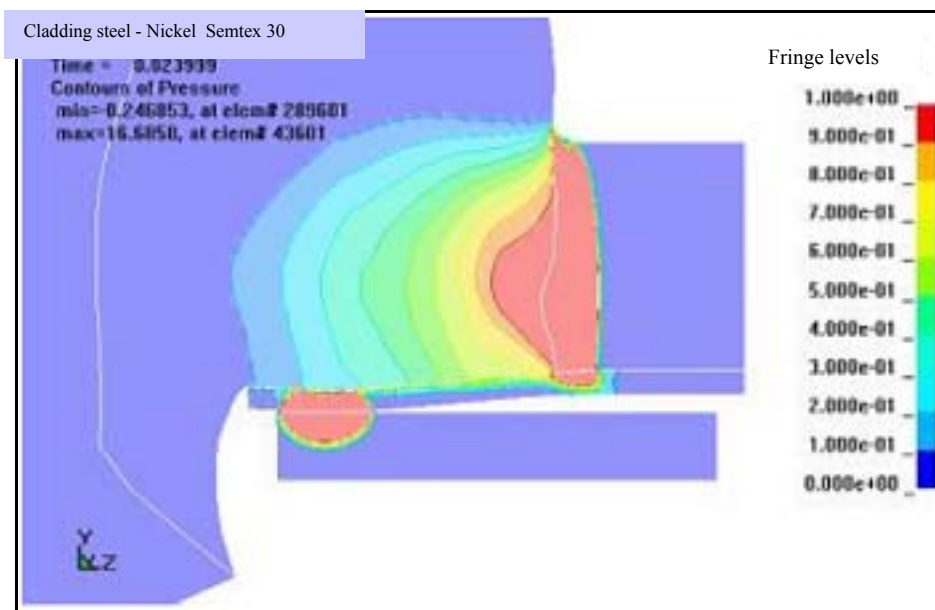


Fig. 7 Numerical simulation of explosive welding.

by means of Roll Technology. Selected combinations of metallic materials is processed by Roll Technology only, or it is possible to utilize EWT for preparation of semi-finished products for subsequent rolling-down. The semi-finished products are usually prepared in the form of bimetallic plates - tool steel and armour steel cladded with suitable interlayer. These plates are subsequently rolled together. The advantage of semi-finished product prepared in this way is the quality weld interface of the bimetal, which facilitates its further processing in roll stand. The semi-finished products for rolling-down can be prepared in almost any size. Dimensions from 2 to 4 m² are common.

Preparation of model multilayer materials by means of explosive welding technology has found its application and serves primarily for a quick testing of some functional properties of the proposed multilayer structure. Various material combinations can be joined in various thickness ratios, but with limitation to the starting materials processed to the form of sheets and plates. Manufacturing of model structures using EWT is relatively quick and not very costly. This enables, within a short time, to prepare multilayer materials in the most various material combinations. After testing of properties and selection of suitable material combination it is possible to start with further production by the follow up technology, in this case roll forming. The scope of material combinations is very wide.

QUALITY CONTROL OF BIMETALLIC AND TRIMETALLIC METALS

Recently, the research in the field of welding the combined metals was carried out. Below are some results of checking the joints quality by optical microscopy and X-ray microanalysis. The results are presented in Figs. 8 –16.

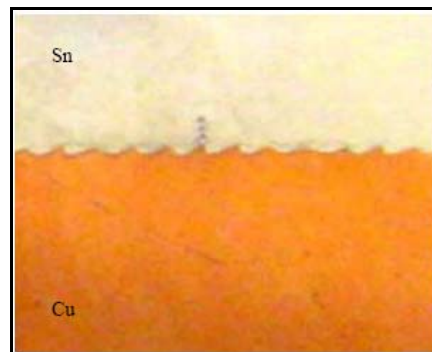


Fig. 8 Macrostructure Cu-Sn.

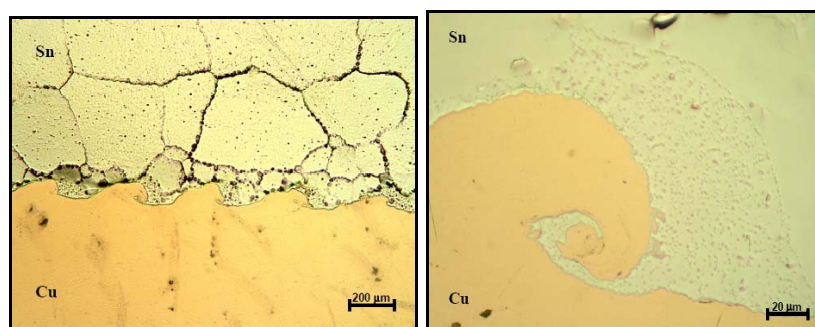


Fig. 9 Microstructures of Cu – Sn interface (Explosive Semtex So12K), $v_d = 1150$ m/s.

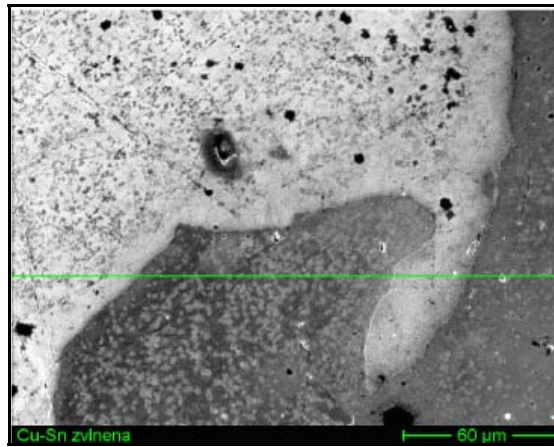


Fig. 10. The course of change in Cu and Sn concentration through the bimetal interface.

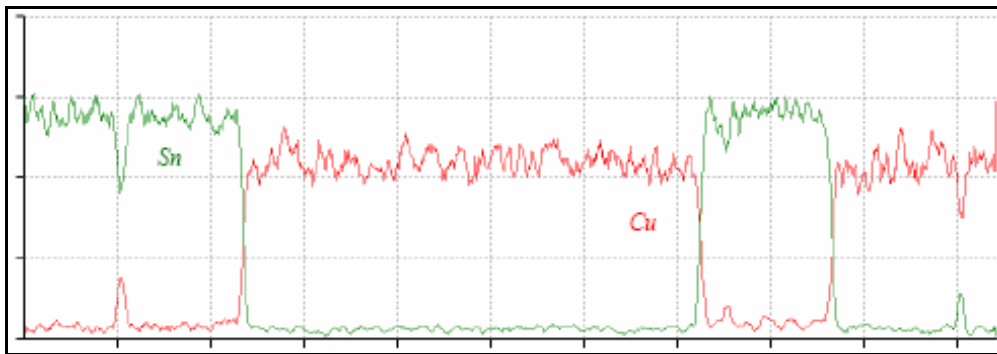


Fig. 11. Cu and Sn line profiles across the weld interface.



Fig. 12. Macrostructure of trimetal (section perpendicularly to the Ti – steel explosion direction and in the Al - Ti explosion direction).



Fig. 13. Microstructure of Ti – Al interface (Keller etching).

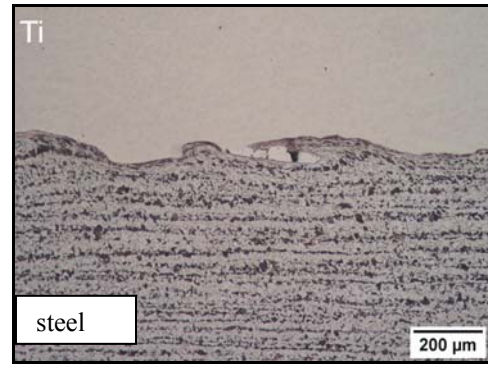


Fig. 14. Microstructure of Ti – steel interface.

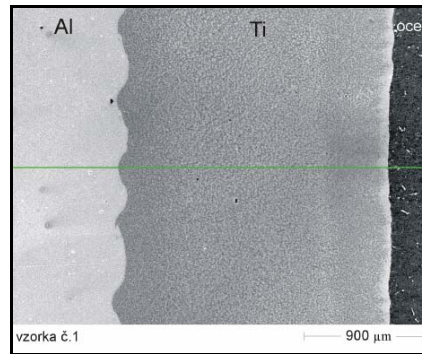


Fig. 15 Measurement area through trimetal Al -Ti - steel interface
 (steel: h=39 mm, Ti: h=2mm, Al: h=16mm, detonation Ti to steel 11 523, $v_d=2190$ m/s, detonation Al to Ti, $v_d = 2705$ m/s, Semtex S 30)

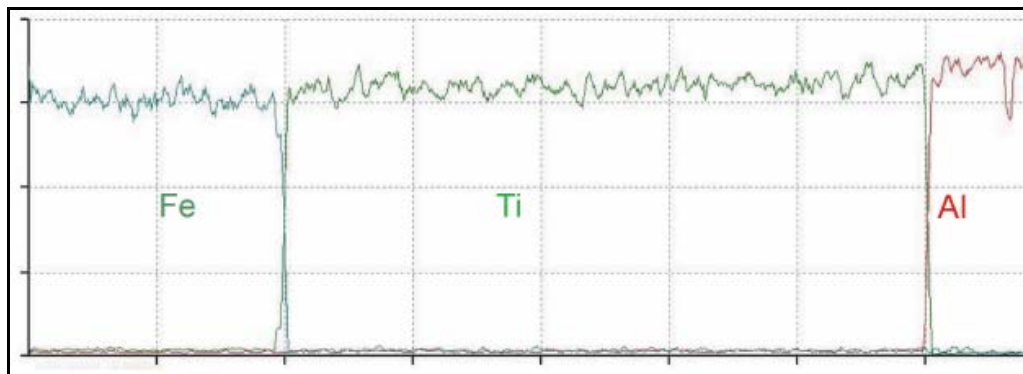


Fig. 16 Course of the change in Al, Ti and Fe concentration through the trimetal interface

CONCLUSIONS

The lecture presents just a part of knowledge from the technological processing of metals by explosion. The most significant results have been implemented into technical practice, a part of results was patented and a part was published. These results will be mentioned in the lecture.

The most recent works were performed in cooperation with RIICH Explosia Pardubice (CR) and are given in the references. The faculty bachelors, graduates working on their thesis and the doctorate graduants were involved in these works.

The specialists of V RIICH Pardubice have a long-year experience in the work with explosives and with technological processing of materials by explosion.

The workplaces of the Faculty of Materials Science and Technology of SUT Trnava and FCHFT SUT Bratislava have available suitable instrumentation, where quality of joints can be assessed by the techniques of optical microscopy, electron microscopy and X-ray microanalysis, applied to their boundary zone (in case of bimetals, trimetals etc.). There are efforts to contribute also to elucidation of mechanism of joint formation in explosion welding and also to enhance the structural stability of the joint boundary.

Special attention will be in the future devoted to formation and growth of intermetallic phases in the boundary zone of combined metals. A suitable software for this purpose is available at the Faculty. Besides the others efforts we also try to oppose the statement of big companies supposing that the small companies dealing with technological processing of materials by explosion have no chance to survive.

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